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SIGNAL CONDITIONING FOR SATELLITE BORNE ENERGETIC-CHARGED-PARTICLE EXPERIMENTS

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SUMMARY

Many of the spacecraft launched thus far have carried detectors for investigating cosmic rays, solar protons, solar plasmas, and the geomagnetically trapped radiation. These detectors, which will find continued application in the future, include ion chambers; proportional, Geiger-Müller, scintillation, Čerenkov, and solid state detectors; ion collectors; and nuclear emulsions. The instrumentation required to condition the signals from these detectors prior to telemetering is steadily growing more complex in order to permit more meaningful measurements. This report describes a number of instrumentation elements typical of the present state of the art, and a present-generation three-detector system which illustrates the integration of such basic elements into a complex system.

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INTRODUCTION

Since the existence of cosmic rays became known in the early part of this century, there have been extensive investigations directed toward learning their characteristics and origin. These investigations have determined some characteristics of the particles, and have also resulted in the discovery of previously unknown elementary particles and physical phenomena. The need to study the primary particles themselves, rather than the secondary products produced by interactions in the high atmosphere, made it necessary to conduct experiments at ever increasing heights — first on mountain tops, then in balloons and rockets. The satellites and space probes which are now available provide a powerful new research tool for conducting experiments where the atmospheric effects can be eliminated completely. Thus, it is now possible to study the primeval cosmic rays as they arrive in the vicinity of the earth.

The satellite observatory has made possible meaningful studies of other charged particle components in addition to the very high energy cosmic rays. The first extensive study of the high energy protons which arrive from the sun after certain solar flares was made with balloon borne instrumentation. These particles have subsequently been studied by rocket and satellite borne instrumentation; and further study of the energy spectra of the radiations and the morphology of events following the flares will lead to a greater understanding of solar physics and the nature of the solar system.

In addition to the high energy particles given off by the sun during these solar flares, it is believed by many that a plasma or "solar wind", containing its own magnetic field, continually distorts the magnetic fields which exist in the region near the earth. This results in a modulation of the arrival of charged particles near the earth. An understanding of the structure and temporal character of this low energy solar component will further clarify the solar-terrestrial relationships.

Perhaps one of the most important single findings of the recent International Geophysical Year was the high intensity trapped radiation (Van Allen Radiation) discovered by the State University of Iowa group through the use of Explorers I, III, and IV (1958α, 1958γ, and 1959δ) and Pioneers III and IV. This discovery has led to a large program aimed at determining in detail the source and methods of capture and release of these particles from their trapped paths.

Thus, the advent of the spacecraft has sparked a new and expanded interest in the study of charged particles in space over the entire energy range from a few electron volts upward. It is certain that charged particle experiments will be carried aboard spacecraft in large numbers for a long time to come. The design, fabrication, and use of detectors and instrumentation systems in satellites and other spacecraft has become a major new field of endeavor, drawing heavily on the techniques of the past but leading also to many improved techniques. New requirements have been imposed on the instrumentation by the extreme physical environments encountered in launching and in space. Spacecraft instrumentation must give reliable and accurate results while operating unattended for long periods; an added complication is the requirement that all data be processed for telemetering over long radio links to the receiving stations. These requirements will continue to lead to instrumentation of ever-increasing complexity. As attempts are made to measure the characteristics of the radiations in still greater detail, more processing of the data in the spacecraft before transmission will become necessary. As a matter of standard practice, certain counting and analysis operations on the output signal of the charged particle detector are now performed within the satellite, in preference to telemetering each event in all its detail for analysis on the ground. This trend is expected to continue to the point where programmable computers aboard the spacecraft will perform complex analyses — since less payload weight would be needed for the computer than to meet the electrical power demands of telemetering very large quantities of raw data. Conservation of ground receiving and data reduction capability will also be a factor in this development.

GENERAL CONSIDERATIONS

Many different detectors exist for the study of energetic particles; Table 1 lists these and indicates their applicability to spacecraft. Most of them rely on the ionization process for their operation: the particle being detected produces ionization in the detector, and the resulting electrons, ions, and photons are gathered and analyzed. Some characteristics of the electrical signals which appear at the detector outputs are also summarized in Table 1. These are the signals which must be prepared for storage or transmission over the telemetry link by the signal conditioning instrumentation.

The raw information must be converted into a form which satisfies the following conditions:

1. The information must be in the most meaningful form practicable.

2. It must be capable of transmission over a telemetry link (except in the case of a recoverable spacecraft).

3. This telemetering must be accomplished within the smallest information bandwidth practicable.

4. The instrumentation must meet the requirements of ruggedness, relatively low power, light weight, and relatively small volume, imposed by the launching vehicle and environment.

5. The instrumentation must be reliable while operating unattended for long periods under conditions imposed by the spacecraft and its environment.

The operations to be performed on the outputs of those detectors which are electronic in nature include amplification (either linear or nonlinear and either pulses or constant amplitudes); shaping; counting of events; measuring of time intervals; conversion from analog to digital form; logic operation ("and" or "coincidence", "exclusive or" or "anti-coincidence", "inclusive or", etc.); sorting; and storage. In addition, all but the simplest signal conditioning instrumentation requires complex controlling and programming operations.

The sections that follow will be concerned with certain signal conditioning instrumentation used in previously launched spacecraft or designed for use in impending spacecraft. The discussion will include equipment used with ion chambers, proportional counters, Geiger-Müller counters, scintillation detectors, Čerenkov detectors, and solid state detectors, but will omit cloud and bubble chambers and nuclear emulsions.

BASIC CIRCUITS

Detectors such as GM counters, in which pulses with approximately fixed characteristics result from any detectable event, often utilize nonlinear amplifiers and pulse shaping circuits to provide optimized driving signals for later circuits and to establish the threshold characteristics. Figures 1, 2, and 3 show several pulse amplifier and shaping circuits used with GM counters to produce driving pulses for counting circuits. The circuit of Figure 1 is a simple current-fed driver which produces a saturating output pulse when the discharge current from the GM tube passes through the base-emitter junction (Reference 1). This very simple circuit contains few components, but

Table 1
Energetic Charged Particle Detectors

Detector Type	Physical Process Utilized	Forms of Output	Characteristic of Output Utilized	Use in U. S. Satellites
Ion Chamber	Ionization of a gas	Pulse	Pulse rate	Used in Pioneer I, V, Explorer VI, VII
			Charge per pulse	
		Integrated current	Charge per unit time	
Proportional Counter	Ionization of a gas and ion multiplication	Pulse	Pulse rate	Used in Pioneer V, Explorer VI
			Charge per pulse	
Geiger Müller (GM) Counter	Ionization of a gas and ion multiplication	Pulse	Pulse rate	Used in Explorer I, III, IV, VI, VII, Pioneer I, III, IV, V
		Integrated current	Charge per unit time	
Cloud Chamber	Ionization and condensation of a supersaturated gas	Visual tracks, recorded by a photographic film or TV system	Rate of events	Not presently feasible because of need for either recovery of film or transmission of high resolution pictures
			Ionization density along track	
			Curvature of track when magnetic or electric fields are applied	
			Study of sequence of interactions and secondary particles produced	
Bubble Chamber	Ionization and vaporization in a superheated liquid	Same as cloud chamber	Same as cloud chamber	Same as cloud chamber
Solid Chamber	Solid scintillator followed by an image intensifier	Same as cloud chamber	Same as cloud chamber	Same as cloud chamber

Table 1

Energetic Charged Particle Detectors

Table 1 (cont.)

Detector Type	Physical Process Utilized	Forms of Output	Characteristic of Output Utilized	Use in U. S. Satellites
Nuclear Emulsions	Ionization from particles produce developable silver halide grains	Visual tracks in body of emulsion usually observed under micro-scope	Same as cloud chamber	Requires satellite re-covery. Used in SBE, NERV, Atlas pod rocket firings
Ion Collector	Direct interception of low energy charged particles	Pulse Integrated current	Pulse rate Charge per pulse Charge per unit time	Used in Explorer X
Scintillation Detector	Ionization or excitation of atoms in a solid and production of photons during de-excitation. Detection of photons by light sen-sitive detector such as photo-multiplier tube	Pulse Integrated current	Pulse rate Pulse shape P.M. Charge per pulse P.M. Charge per unit time	Used in Explorer IV, VI, Pioneer V
Čerenkov Detector	Čerenkov radiation in a solid. Detection of the photons by light-sensitive detector such as photo-multiplier tube	Pulse	Pulse rate P.M. Charge per pulse Direction of propa-gation of photons	To be used in near future. Has been used in USSR space-craft
Solid State Detector	Ionization of atoms in a solid with resultant change of body conductivity Ionization of atoms in a solid and transport of resultant electrons across a potential barrier (junction)	Resistance Pulse	Conductivity Pulse rate Voltage amplitude of pulse	To be used in near future

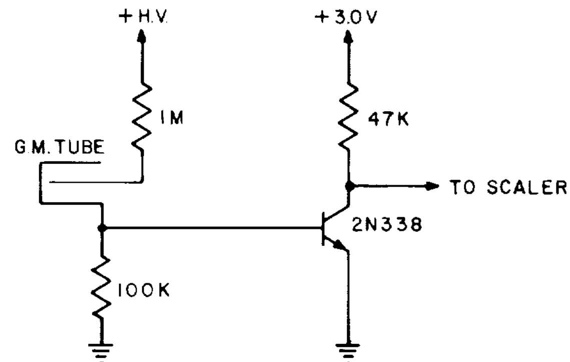


Figure 1 - Early State University of Iowa (SUI) current-fed GM tube driver circuit

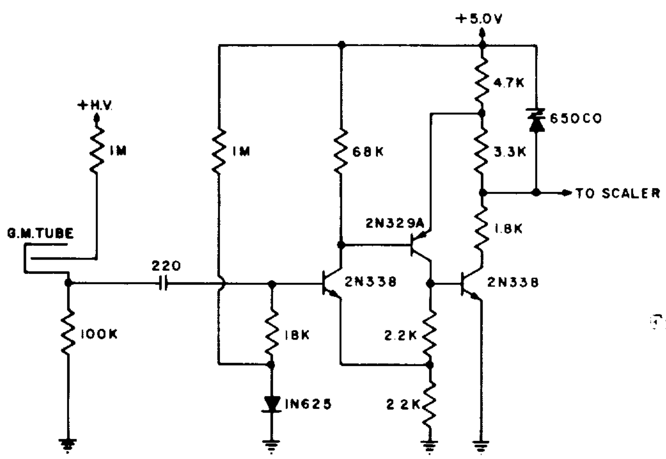
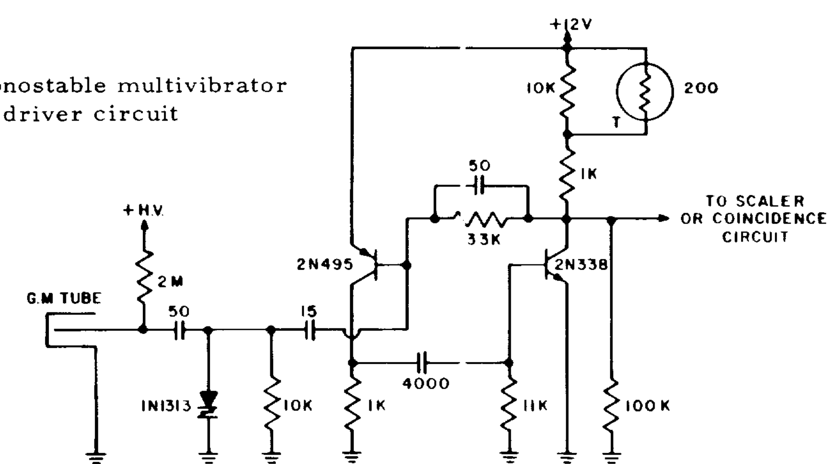


Figure 2 - Compensated SUI GM tube driver circuit

Figure 3 - Monostable multivibrator GM tube driver circuit



has the disadvantage that the system dead-time characteristics depend on the pulse amplitude and dead-time characteristics of the counter and on the pulse amplitude threshold of the scaler input; and these in turn both depend to some extent on the supply voltages and the temperature. To reduce these effects in applications where the counting rate is expected to exceed 30 percent of the GM tube maximum counting rate, the circuit of Figure 2 was developed (Reference 2). It is a two-stage "bootstrap" amplifier with a stable gain characteristic and a high impedance transformation ratio. It includes a differentiating circuit to produce a voltage pulse at the input, and a Zener diode at the output to regulate the output pulse amplitude. When used with type 213, 223, 302, or 112 halogen-quenched GM tubes and the scaling circuits of Figure 4, it results in essentially flat counting-rate vs. temperature and counting-rate vs. primary power supply voltage characteristics at the maximum counting rate.

The circuit of Figure 3 is another approach to the same problem (Reference 3). It utilizes the voltage pulse obtained from the center wire of the GM tube to trigger a monostable multivibrator. Thus, the total dead time is determined, to a first approximation, by the sum of the multivibrator pulse width and recovery time.

The counting, or scaling, circuits shown in Figures 4, 5 and 6 all meet the requirements of simplicity and operation over a wide temperature range. All require a power of less than one milliwatt per stage. Figure 4 (References 2, 4 and 5) shows a very simple circuit which can be used whenever the counting rate is not to exceed 5000 per second and whenever a low output impedance is not required. This circuit can drive two similar circuits with no interposed circuitry, as can the others discussed below. Its attractiveness lies in the very small number of components required. It operates reliably over the temperature range from -50° to +90°C and over the supply voltage range from 4.5 to 8 volts. When faster operation is necessary, a modification of this circuit can often be used whereby the collector and cross coupling resistors are reduced in size and the time constant of the pulse steering circuit is reduced as shown in Figure 5. This circuit still requires less than one milliwatt per stage (Reference 2).

When even higher operating speed or low output impedance is required, the complementary symmetrical scaler shown in Figure 6 is often used (Reference 6). In this circuit the fixed collector resistors of Figure 4 are replaced by transistors in a configuration wherein one transistor in each branch is cut off and the other is conducting. Therefore, the output impedance and the current are low in both stable states. Circuits of this type have been used at rates up to 250 kc over the temperature and voltage ranges of -30° to +90°C and 4.5 to 12 volts respectively.

Linear pulse amplifiers are required to amplify by a known and constant factor the pulses from ion chambers, proportional counters, scintillation detectors, Čerenkov detectors and solid state detectors. Owing to the strong dependence of transistor parameters on operating conditions, large amounts of negative feedback are necessary

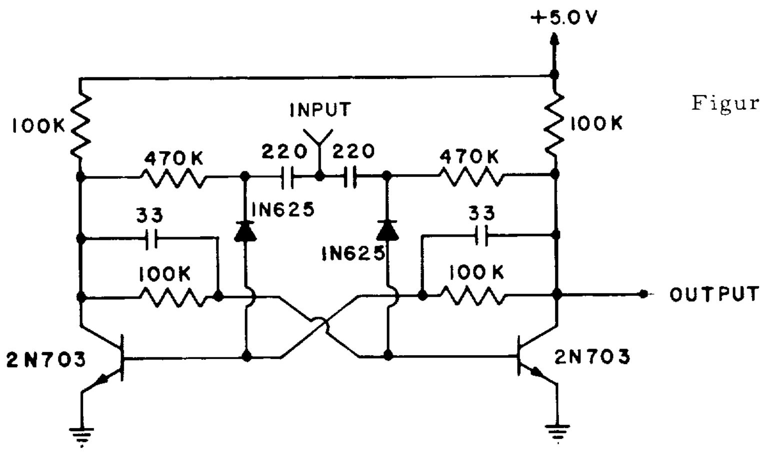


Figure 4 - Basic two transistor scaler

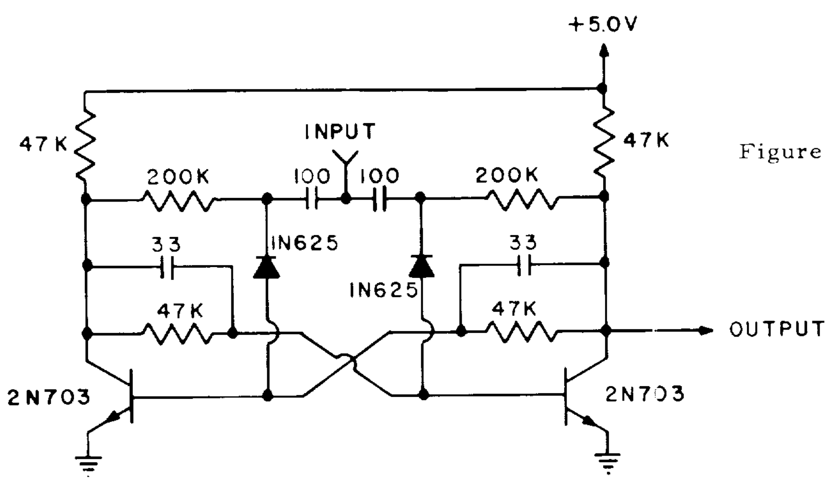


Figure 5 - Medium speed SUI scaler

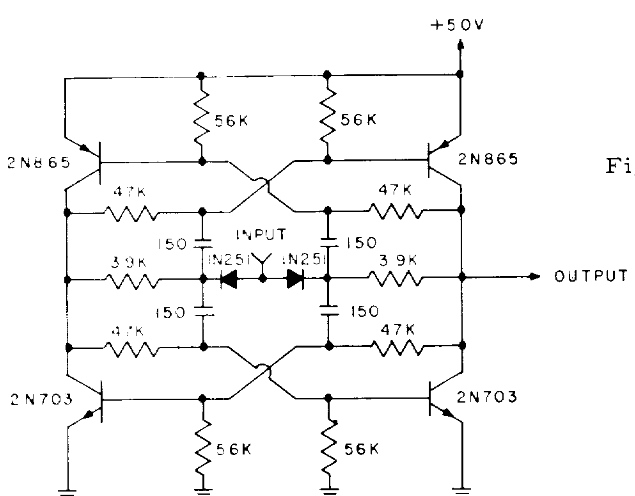


Figure 6 - Complementary symmetric scaler

to stabilize the amplifier characteristics. This also helps to improve the high frequency response of the amplifiers. Figures 7 through 10 show several linear pulse amplifiers. Figure 7 shows a basic "bootstrap" dc-coupled amplifier (Reference 2) in which the gain depends almost entirely on the ratio $(R_1 + R_2)/R_2$. The pulse amplifier shown in Figure 8 was used in Explorer IV with a scintillation detector (Reference 7). The thermistor in the input stage was used to introduce a temperature dependence to balance the photomultiplier tube characteristic, and thereby produce a flat temperature characteristic for the system. The gain of this amplifier was 150, the rise time was 0.3 microsecond, and the operating power was only 10 milliwatts.

Another fast linear pulse amplifier* is shown in basic form in Figure 9. This is an operational amplifier in which the gain is, to a first approximation, $-R_1/R_2$ if the load impedance is high, and is essentially independent of the other circuit parameters. A two stage amplifier and emitter follower with an overall gain of 100 is shown in Figure 10. Both amplifiers shown in Figures 7 through 10 possess high input and low output impedance and linear operation at frequencies higher than 1 Mc. They can be used with other pulse detectors by properly adjusting the number of stages and stage gains, and by providing a suitable input circuit.

Frequently it is necessary to convert an analog voltage or current to a digital signal. In some cases it is possible to perform this operation in the detector itself, as in the Neher self-integrating pulse ion chamber. In this device a coated quartz fiber is given an electrostatic charge which causes it to be deflected from the charging post. The rate of leakage of the charge depends on the amount of ionization produced in the chamber. When the charge is neutralized, the fiber again touches the charging post, acquiring a new charge and producing a pulse at the chamber output. Thus the pulse rate is proportional to the total ionization produced in the chamber.

Often, auxiliary circuits are used to perform a similar conversion of integrated current to pulse rate for other detectors. Figure 11 shows a simple relaxation oscillator used to convert current in the range from 10^{-5} to 10^{-9} ampere to a pulse rate (Reference 2). This technique has been applied to the measurement of current through cadmium sulfide solid state detectors, of the integrated ion current in an ion chamber, and of the integrated dynode current in a scintillation counter. By proper choice of the circuit components, stable operation can be obtained over a wide temperature range. The circuit as shown in Figure 11 cannot be used to measure currents smaller than 10^{-10} ampere because a current this small can pass through the discharge tube without causing a complete discharge. A simple modification can be made, however, to permit measurement of currents lower by several orders of magnitude. This is accomplished by superimposing a low amplitude periodic waveform on the discharge element. A

*This amplifier forms part of the Radiation Instrument Development Laboratory's 32-channel satellite pulse-height analyzer.

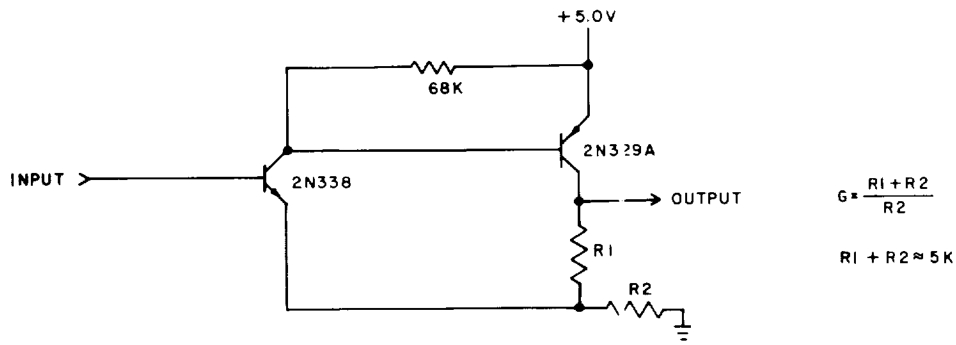


Figure 7 - Basic "bootstrap" amplifier

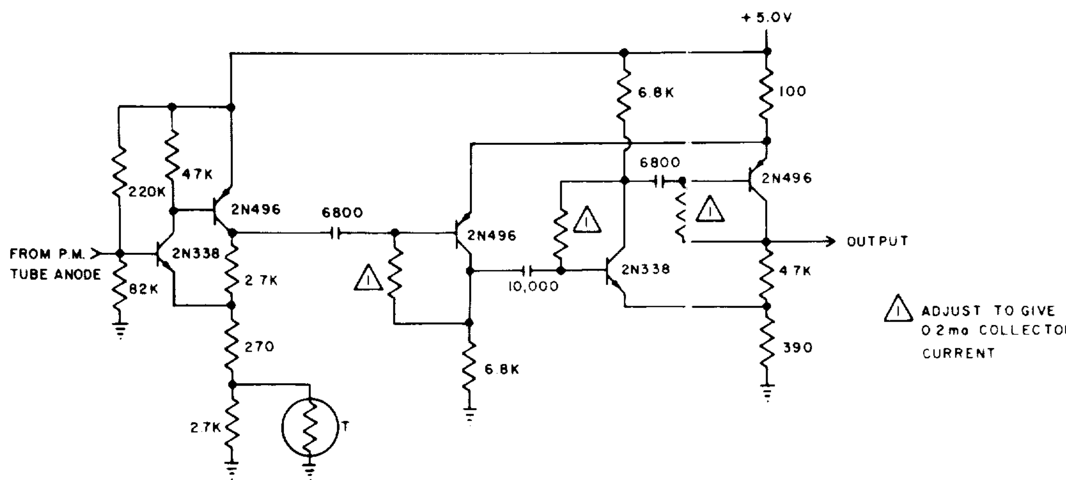


Figure 8 - Linear pulse amplifier for the SI I scintillation counter

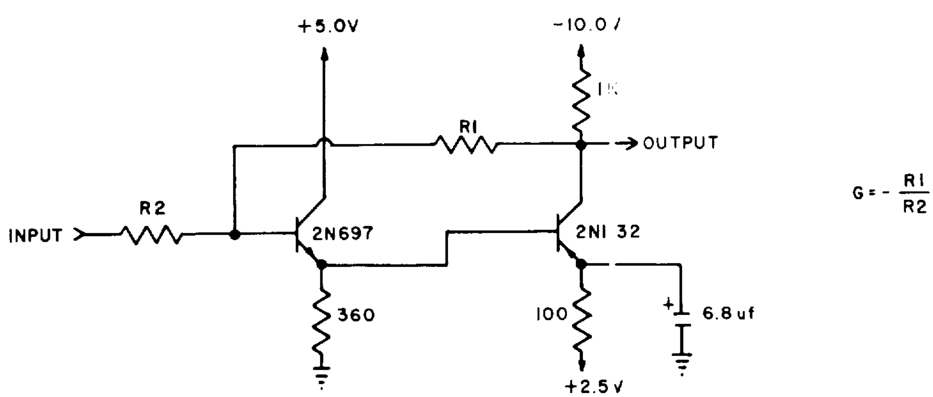


Figure 9 - Basic operational linear amplifier

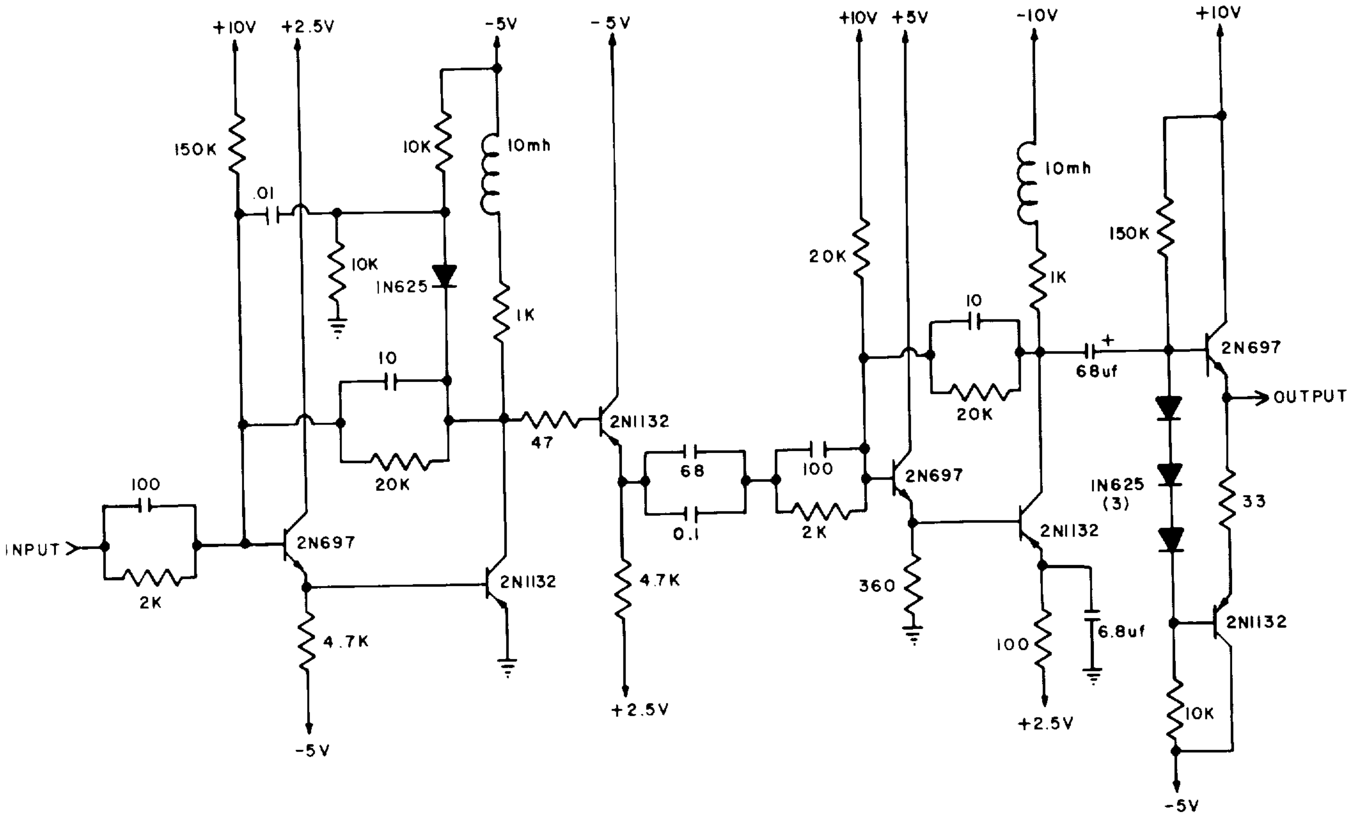


Figure 10 - Radiation Instrument Development Laboratory linear pulse amplifier

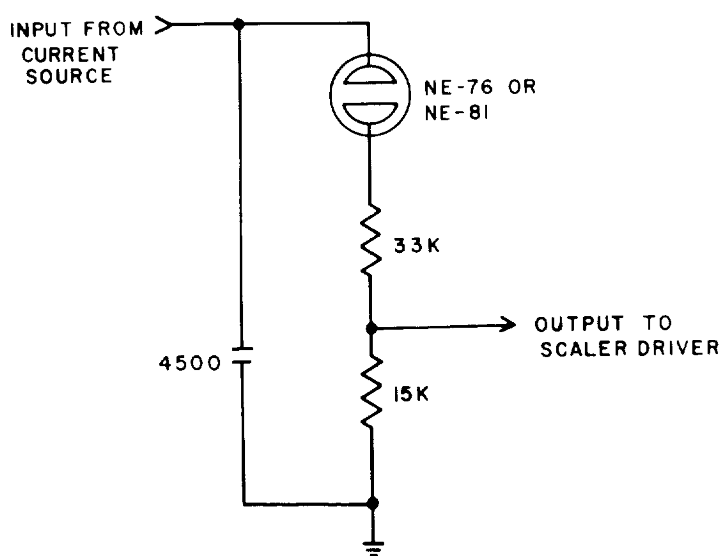


Figure 11 - Current measuring relaxation oscillator

circuit employing an auxiliary relaxation oscillator to generate this waveform (Reference 8) is shown in Figure 12. This circuit is capable of measuring currents to about 10^{-12} amperes.

A voltage amplitude can be converted from analog to digital form by means of the circuit shown in block diagram form in Figure 13. It can be used as shown for inputs having variations that are slow compared with the clock rate. If this is not the case, a pulse lengthener or level-clamping circuit can be used to hold the level for the duration of the measurement. Action is started by applying a "begin conversion" pulse which opens the clock gate. The scaler counts the clock pulses until the stairstep level first exceeds the input amplitude. At this point a comparator output appears which closes the clock gate. The amplitude is then contained in digital form in the scaler and can be commutated, shifted out, or used directly to address a storage matrix.

The pulse height-to-time converter shown in Figure 14 contains a different type of analog-to-digital converter in which a capacitor is charged initially to the input amplitude and a clock gate is opened (Reference 9). The capacitor is permitted to discharge at a constant rate until its voltage reaches a threshold value, then the gate is closed. Thus, the gate width is proportional to the input voltage minus the threshold voltage. The gate allows clock pulses to be counted by a scaler, and at the end of the conversion the digital number again resides in the scaler. The conversion speed is the same as that of the circuit of Figure 13. Both this and the previous circuit can utilize a zero offset, by biasing the stairstep off-zero in the one case (Figure 13) and by making the threshold voltage non-zero in the other (Figure 14). Much faster conversion can be obtained by using a successive approximation technique in which one bistable stage is set at a time. The stages generate a stairstep voltage in the same manner as the circuit of Figure 13. The stage giving the largest change in the output (from zero to half maximum amplitude) is set first. If the resulting stairstep voltage is less than the input amplitude, that stage is left in the set position, but if more, it is reset. A similar procedure is followed sequentially for the other stages. At the completion of the conversion the digital number resides in the scaler as before; but instead of a maximum of 2^n clock pulses, where n is the number of scaler stages, only n clock pulses are required. Thus, this circuit can perform the conversion described above in 14 rather than 256 microseconds.

Often it is desirable to include some form of data storage in the satellite. Short term storage is used to hold data until they can be used by the satellite signal conditioning system, or until they have been sampled one or more times by an operating time-multiplexing telemetry system. Long term storage is used to permit the accumulation of significant data before processing, and the recovery of data over the full satellite orbit by a small number of ground receiving stations. The data storage system may be considered part of either the signal conditioning system or the spacecraft data handling system, depending on the nature of its application. If used as an integral part of a single

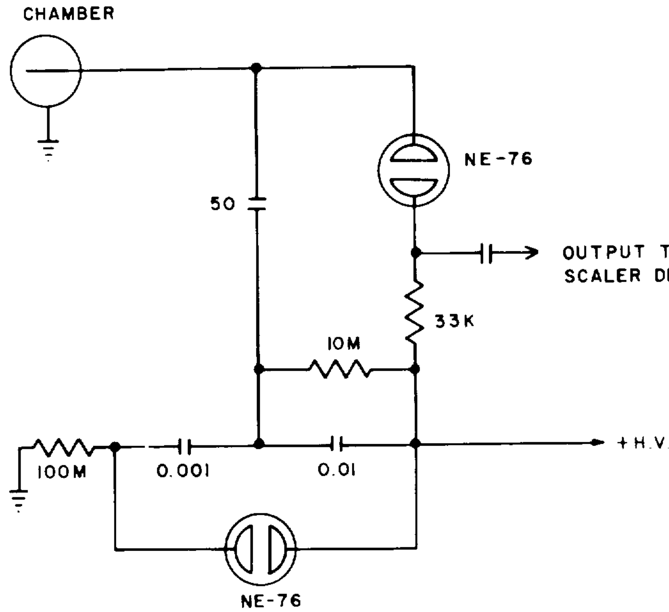


Figure 12 - Low-current measuring relaxation oscillator

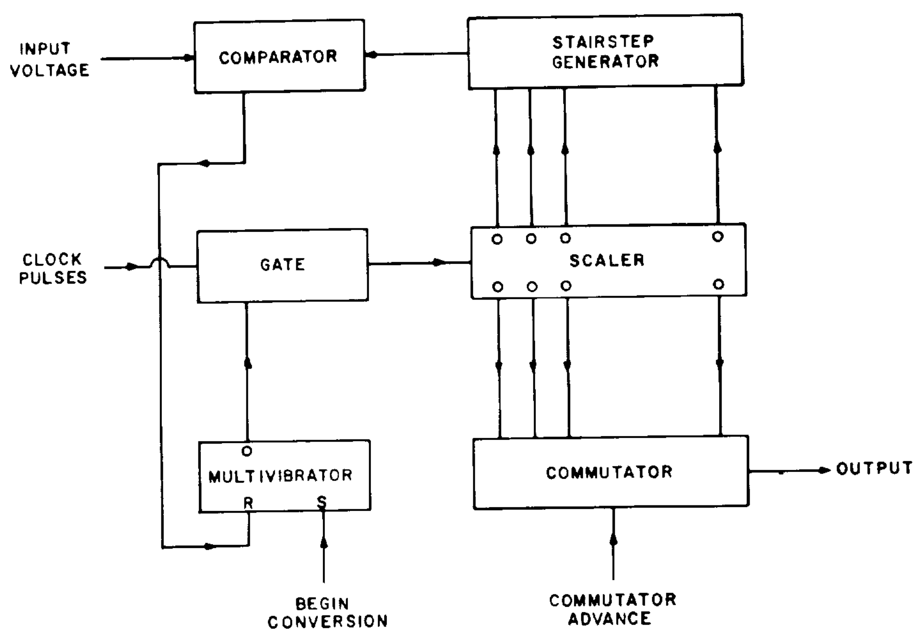


Figure 13 - Stair-step type analog-to-digital converter

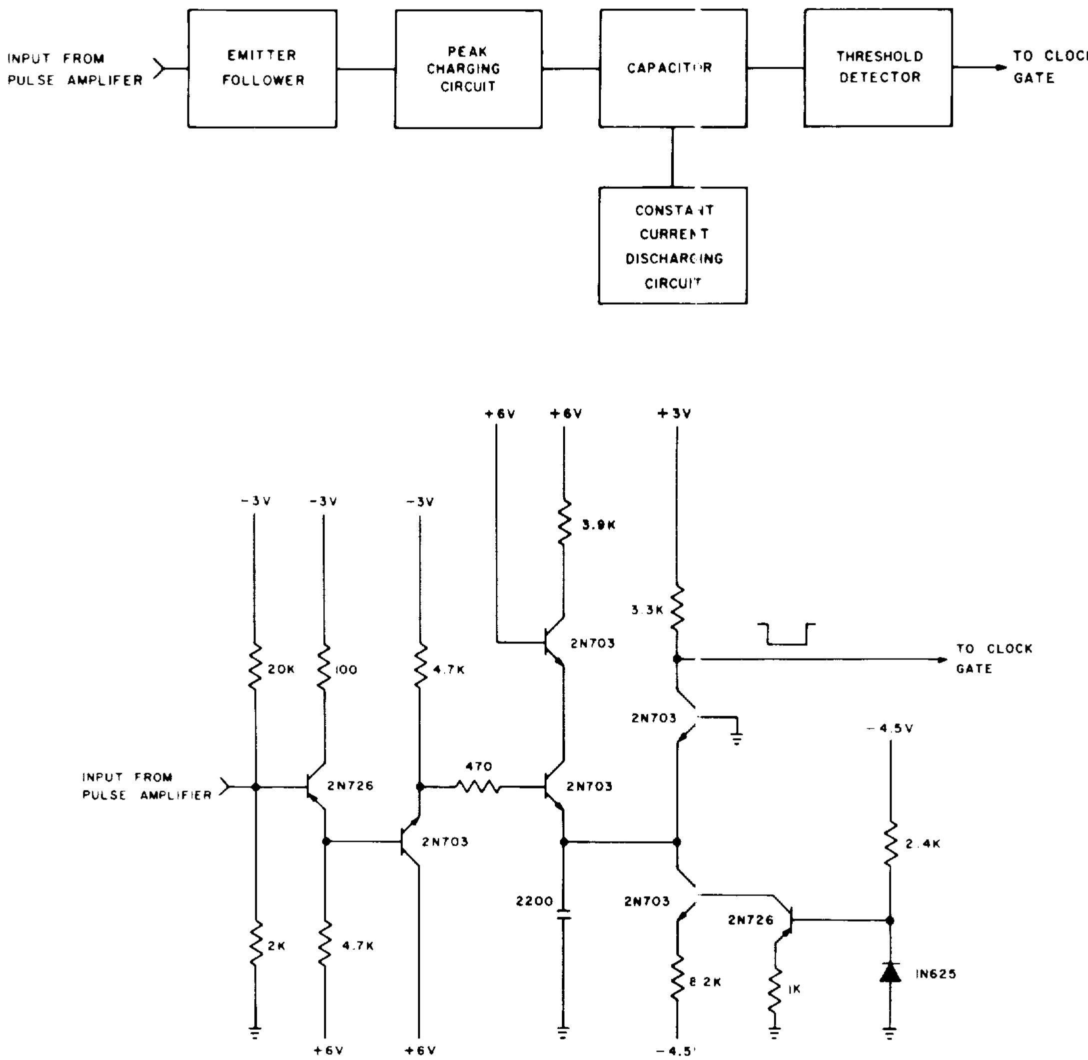


Figure 14 - Ramp pulse height-to-time converter

experiment, it is usually designed into the conditioning system. But if it is a central system used by a large fraction of the experiments, it is considered a part of the telemetry system.

Commonly used forms of storage include capacitors, bistable multivibrators, magnetic cores, and magnetic tape for digital data; and magnetic tape for analog data. Bistable multivibrators are used for storage of up to tens of binary bits, magnetic cores for hundreds to thousands of bits, and magnetic tape for tens of thousands to tens of millions of bits. A circulating magnetostrictive delay-line storage is currently being developed for storage of 10,000 bits.

SIGNAL CONDITIONING SYSTEMS

In a spacecraft the detectors and signal conditioning circuit elements must be so assembled that meaningful data can be sent to the ground stations from a number of detectors, often over a single telemetry system. Thus, either time division or frequency division multiplexing is usually used. Often, data from one detector are accumulated while data from another detector are being telemetered. To illustrate: the pulse height spectrum from a scintillation counter may be analyzed and accumulated in a magnetic core storage matrix while data from a GM counter, previously stored in a scaling circuit, are being transmitted. Most energetic particle detectors are adaptable for use in a time sharing mode of operation. In those rare cases wherein full time telemetry is required, the data are either frequency multiplexed as in, for example, an FM/FM system, or a separate transmitter is provided.

To illustrate the manner in which data from a number of different types of detector are analyzed, stored, and multiplexed onto a common telemetry link, the subject of the remainder of this discussion will be a present-generation spacecraft instrumentation system designed to study primary cosmic rays and energetic solar protons. The experiments, designed at the Goddard Space Flight Center, had the following objectives: (1) to assist in the study of the cosmic ray accelerating mechanism; (2) to study the nature of the modulation mechanisms which result in the eleven year variation and the Forbush decreases which accompany certain forms of solar activity; and (3) to increase understanding of the mechanism by which solar cosmic rays are produced and modified by solar weather. The instrumentation is shown in block diagram form in Figure 15.

The first detector, a double scintillator telescope, is capable of measuring the proton spectrum in the range from 70 to 700 Mev. Only particles traversing both elements of the assembly are processed. When a coincidence is obtained, the pulse from one of the scintillator detectors is analyzed by a pulse height analyzer, which sorts the pulses into 32 storage channels depending on which of 32 amplitude increments they fall

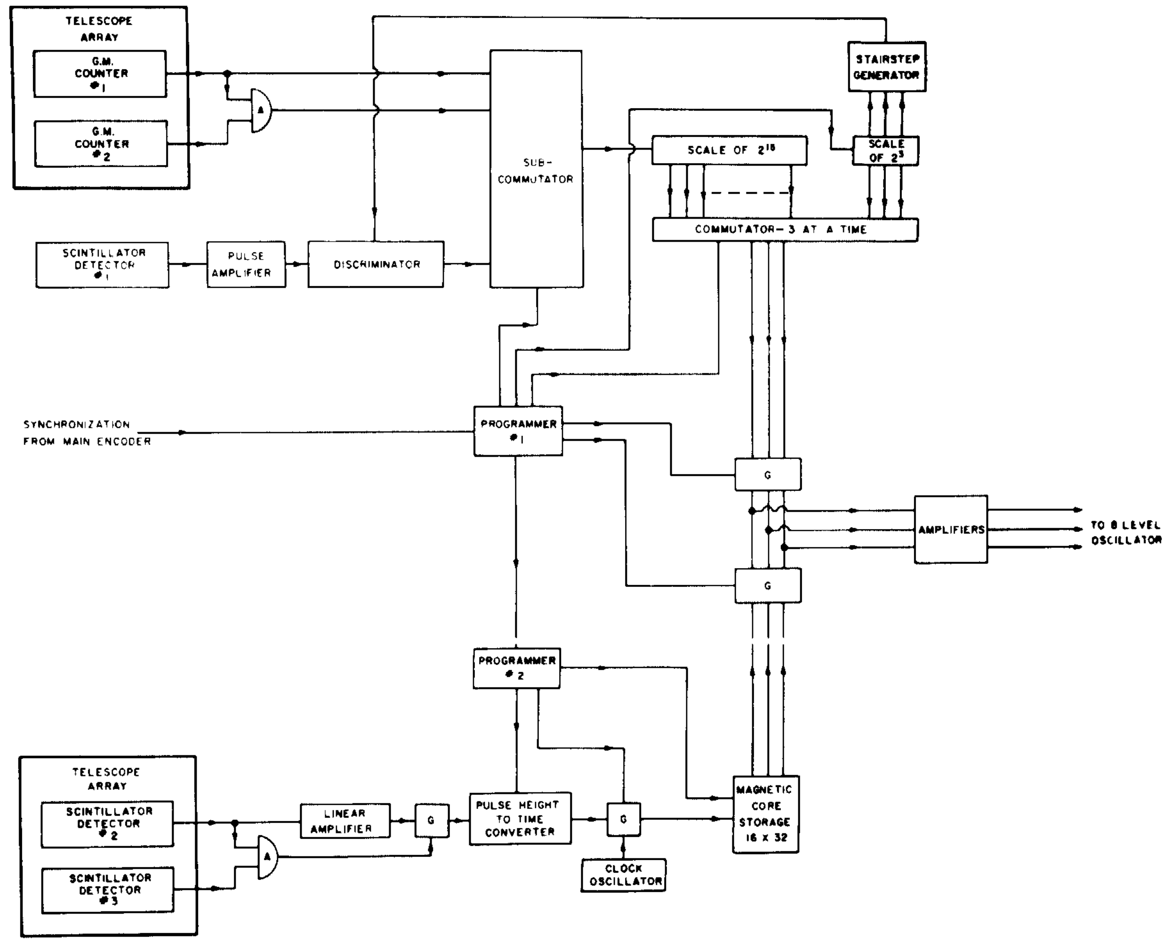


Figure 15 - Three detector charged particle experiment

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within. The analyzer utilizes the linear pulse amplifier of Figure 10 and a pulse height-to-time converter of the type shown in Figure 14. The gated clock pulses are counted in the address register of the magnetic core storage matrix. At the completion of this counting operation one count is added to the number contained in the channel addressed by the address register. At the completion of the store mode, the complete pulse height spectrum (differential energy spectrum) is contained within the 16 by 32 core matrix. During the readout mode these 512 binary bits are sequentially telemetered. The pulse height analyzer as described above has been designed for use in spacecraft by the Radiation Instrument Development Laboratory and is available in a package measuring $6 \times 6 \times 5$ inches, weighing 5.5 pounds, and requiring about one watt of power.

The second detector used in this system of instrumentation to extend the proton energy spectrum down to about 1 Mev is a thin CsI scintillator detector. The pulse height distribution from this detector is determined by an eight-channel sliding-window integral pulse height analyzer developed at GSFC (Reference 6). In this analyzer, a pulse amplitude discriminator level is established by an eight-level stairstep generator. All pulses with amplitudes greater than the discrimination level are counted by a scaler. At each stairstep level the pulses are accumulated and then read out. The discriminator is sequentially stepped through its eight levels.

The third detector consists of two Anton type-1003 "Pancake" GM counters arranged to serve as a simple, reliable, cosmic ray monitor and to check the information received from the other two detectors. The counters are arranged in a telescope array; and the coincidence rate and the rate from a single GM counter are accumulated and telemetered sequentially.

A commutating system is included to allow all three detectors to utilize common telemetry channels. At the beginning of the commutation cycle the GM counter coincidence events are accumulated for about 1.6 seconds and read into the telemetry system during the following 0.96 second. Then the single GM counter output is accumulated and read for comparable time intervals. The output of the single scintillator detector, with the discriminator set at the first stairstep level, is accumulated and read during the next 1.6 and 0.96 second periods respectively. This is repeated for stairstep levels two through eight. Thus, 25.6 seconds are required to read the counting rates of these two detectors. This sequence is repeated 12 times, requiring a total of slightly more than 5 minutes.

During the time the GM counter and single scintillator detector rates are being read, pulses from the double scintillator telescope are analyzed and stored in the magnetic core memory. At the completion of this sequence, the data lines to the telemetry system are switched to the analyzer storage system, and its readout begins. The stored data are telemetered several times during the ensuing 102 seconds. Thus, a new energy

spectrum analysis and a complete set of GM telescope and single scintillation detector data are obtained every 6.7 minutes.

The subsystem outlined above, including the pulse height analyzer, was fabricated in the form of five subassemblies utilizing approximately 530 transistors, weighing 12.8 pounds, and requiring 1.4 watts of electrical power. It forms a part of the complete satellite payload which also contains instrumentation to study the geomagnetically trapped radiation, solar plasmas, and the magnetic field in the region from several hundred kilometers above the earth's surface to more than ten earth radii.

CONCLUDING REMARKS

Most of the satellites and space probes launched up to the present time have carried instruments designed to study the energetic charged particles. Because studies of these particles can yield information about the relative abundance of the elements in the universe; magnetic and electric fields in this and other galaxies and near the sun, earth, and other planets; and the physics of stars, planets, and their atmospheres; and because an understanding of the radiation hazards to manned space flight must be obtained before these flights will occur — it is obvious that charged particle detectors will continue to be used extensively. The complexity of the signal conditioning instrumentation has increased in the three years since the first satellites. That tendency is likely to continue. Information from present experiments continually indicates the need for new experiments, and these result in either the discovery of new and unexpected phenomena or the need for still more definitive experimentation. As the process continues, it becomes necessary to handle ever increasing amounts of data. The present rate of increase in the quantity of data from spacecraft experiments exceeds the present growth rate of spacecraft telemetry system capability. Thus, more and more data conditioning must be accomplished in the spacecraft. Eventually, it is expected, this tendency will lead to the requirement for complex programmable computers on spacecraft, to perform preliminary reduction and analysis and a partial determination of the significance of the data. Of course, this can only become possible as more is learned about the phenomena being investigated. It will always be necessary to include provisions for detecting unexpected phenomena whose data handling requirements may not be accurately predictable.

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